

The very first Pop III stars and their relation to bright $z \approx 6$ quasars

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Abstract.

We discuss the link between dark matter halos hosting the first PopIII stars formed at redshift $z > 40$ and the rare, massive, halos that are generally considered to host bright $z \approx 6$ quasars. We show that within the typical volume occupied by one bright high- z QSO the remnants of the first several thousands PopIII stars formed do not end up in the most massive halos at $z \approx 6$, but rather live in a large variety of environments. The black hole seeds planted by these very first PopIII stars can easily grow to $M > 10^{9.5} M_\odot$ by $z = 6$ assuming Eddington accretion with radiative efficiency $\epsilon \approx 0.1$. Therefore quenching of the accretion is crucial to avoid an overabundance of supermassive black holes. We implement a simple feedback model for the growth of the seeds planted by PopIII stars and obtain a $z \approx 6$ BH mass function consistent with the observed QSO luminosity function.

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INTRODUCTION

Population III stars formed in the early universe at redshift $z > 20$ with a top-heavy initial mass function (e.g. see [1]) are expected to leave at the end of their lives intermediate mass black remnants of the order of $100 M_\odot$. These seeds, formed within dark matter halos of mass $\approx 10^6 M_\odot$, may be the starting points for accretion that will lead to supermassive black holes ($M_{BH} > 10^9 M_\odot$), which are considered to power the luminosity of QSOs, observed in the Sloan Digital Sky Survey (SDSS) at $z > 6$ when the universe was less than one billion years old (e.g. see [2]). These bright QSOs are extremely rare objects (one object per about 200 deg^2 in SDSS, see [2]), so we expect on average one per 1 Gpc^3 comoving.

Within this volume the QSO may either be the descendant of the first intermediate mass black hole seed left from the *first* PopIII star, which would therefore give the most time for mass accretion, or sit at the center of the most massive structure at $z \approx 6$. Of course these two alternatives are in principle mutually non-exclusive, as the remnants of the first PopIII stars could end up in the most massive dark matter halos at $z \approx 6$. This possibility seems to be implied by a number of recent papers, where the progenitor halos of bright quasars are traced back in time and identified as the first dark matter halos formed in the universe (e.g. see [3], [4], [5]). However these works either do not have the mass resolution to identify the dark matter halos hosting the first generation of PopIII stars or rely on multiple mesh refinements of a small region centered around the largest halos identified at $z=0$ in order to resolve scales down to $10^6 M_\odot$.

To properly address the link between bright quasars and PopIII stars it is necessary to resolve a dynamic range in mass of more than 10^{13} : a simulation box of 1 Gpc^3 contains a mass larger than $10^{19} M_\odot$ and within this box dark matter halos below $10^6 M_\odot$ need to be identified. Therefore we have adopted an original approach (see [6]), broadly based on the tree method by [7]. The idea is based on coupling a numerical simulations of structure formation to identify dark matter halos at $z \approx 6$ with a Monte Carlo method to sample subgrid fluctuations of the initial Gaussian random field of density fluctuations at the mass scale typical of halos hosting PopIII. This allows us to attach to every particle in the simulation, which has typically a mass in excess of $10^{10} M_\odot$, the formation time of its first PopIII star progenitor. The details of the method are presented in detail in [6] along with an extensive set of tests to validate our innovative approach. Here we focus instead on summarizing the main results from our investigation.

In particular we show that the first PopIII progenitor of a $z = 6$ bright QSO, while born at $z > 40$ well within the early era of PopIII formation, it is not the first PopIII in the typical Gpc^3 volume occupied by the QSO, but it is rather preceded by about 10^4 other PopIII stars. A qualitative understanding can be reached from simple considerations based on the properties of Gaussian random fields deriving from the spectrum of primordial density perturbations: small mass dark matter halos are sensitive to higher frequency in the density fluctuations spectrum than their higher mass counterparts. Therefore the first $10^6 M_\odot$ dark matter halos formed at $z > 45$ in a simulation box will not in general evolve to become the first

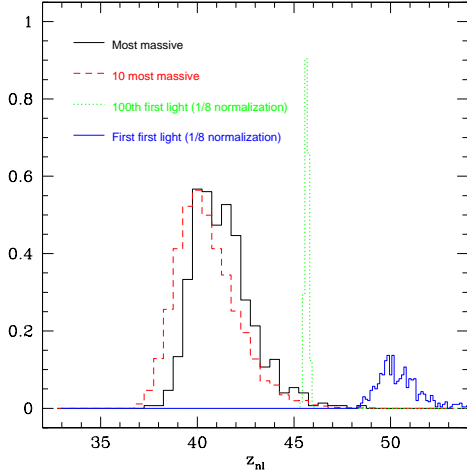


FIGURE 1. From [6]: Distribution of the collapse time z_{nl} for the oldest PopIII progenitor (with $M_{fs} = 10^6 M_\odot/h$) of the most massive halo (black line) and averaged over the 10 most massive halos (red line) at $z = 6$ in the $(720 Mpc/h)^3$ box simulation. The blue line represents the collapse redshift of the *first* PopIII star perturbation, while the dotted green line refers to the collapse redshift of the 100th PopIII in the box.

$10^{12} M_\odot$ dark matter halos formed at $z \approx 6$.

In terms of intermediate mass black hole growth from PopIII this result implies that there are a number of seeds formed in the early universe before the one that will become the bright $z=6$ QSO. All these seeds have enough time, if accreting at Eddington limit with accretion efficiency $\varepsilon \approx 0.1$ to become supermassive ($M_{BH} > 10^9 M_\odot$) by $z=6$. We follow their evolution and we show with a simple accretion model that the gas supply available for growth is limited for most of these seeds, so that the QSO luminosity function derived in our framework is consistent with the slope of the observed QSO luminosity function.

NUMERICAL SIMULATIONS

We identify the largest dark matter halos at $z = 6$ in three cosmological simulations with 512^3 particles and different box sizes: a large (edge $720 Mpc/h$), a medium (edge $512 Mpc/h$) and a small (edge $60 Mpc/h$) box. The simulations have been carried out with the public version of the tree-PM code Gadget2 [8] and a cosmology based on third year WMAP data [9]: $\Omega_\Lambda = 0.74$, $\Omega_m = 0.26$, $H_0 = 70 km/s/Mpc$, where Ω_m is the total matter density in units of the critical density ($\rho_c = 3H_0^2/(8\pi G)$) with H_0 being the Hubble constant (parameterized as $H_0 = 100h km/s/Mpc$) and G the Newton's gravitational constant. Ω_Λ is the dark energy density. In generating

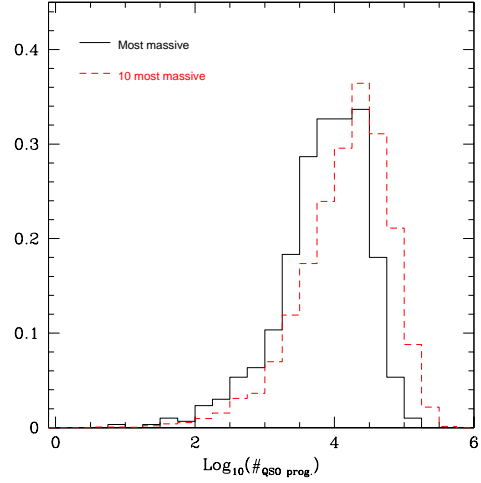


FIGURE 2. From [6]: Distribution for the ranking of the collapse epoch for the oldest PopIII halo progenitor of the most massive halo (black line) and averaged over the 10 most massive halos (red line) at $z = 6$ in the $(720 Mpc/h)^3$ box simulation.

the initial density field we use a scale invariant long-wave spectral index ($n = 1$) of the power spectrum of density fluctuations and $\sigma_8 = 0.9$ or $\sigma_8 = 0.75$ (the root mean squared mass fluctuation in a sphere of radius $8 Mpc/h$ extrapolated at $z = 0$ using linear theory). As described in [6], the initial density field is then used as input in our Monte Carlo code to obtain the formation redshift of the first PopIII progenitor of each particle in the simulation box.

RESULTS

Under the assumption that the first PopIII stars in the universe have formed in $10^6 M_\odot$ halos cooled by molecular hydrogen, the progenitor of the most massive $z = 6$ halo (the one assumed to host the bright QSO) in our large box simulation is born at $z \approx 41$, while the first PopIII in the volume is already present at $z > 49$ (see Fig. 1). By the time the QSO progenitor is born, there are on average 8000 other PopIII stars formed in the simulation (see Fig. 2), with a typical PopIII star formation rate, as obtained from our method, shown in Fig. 3. If PopIII stars reside in halos of different mass and/or if the value of σ_8 is different, there will be a shift on the formation time of these first stars (that is on the scale of the x-axis in Figs. 1-3), but the relative ranking between the *first* PopIII star in the box and the PopIII that is the QSO progenitor remains essentially unchanged (e.g. see Fig. 3 in [6]).

The relation between PopIII and QSOs can be easily

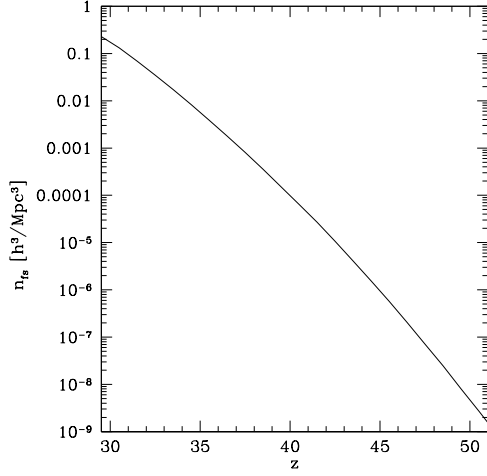


FIGURE 3. From [6]: Comoving number density of virialized PopIII halos ($M_{fs} = 10^6 M_\odot/h$) per unit redshift versus redshift for $z > 29$ as measured by means of our MC code.

understood in terms of the statistics of Gaussian random fields (see Fig. 4). In fact, the most massive $z = 6$ halo in the simulation box (with mass $M_{qh} \approx 4.3 \times 10^{12} M_\odot$) originates from a $\approx 6\sigma(M_{qh})$ peak in the density perturbation field. If we now consider a random volume in the simulation box with mass M_{qh} , we find that the distribution for the maximum peak at the mass scale of a PopIII halo ($10^6 M_\odot$) inside this volume is in the range $[23 : 27]\sigma(M_{qh})$ at the 90% confidence level. This is essentially because (i) we are at a smaller mass scale, so there is additional power in the density fluctuations field and (ii) we are considering here the first PopIII halo formed in the M_{qh} volume, that is the maximum among 160^3 fluctuations. The probability distribution for the peak associated to the first PopIII progenitor of the QSO (green dashed line in Fig. 4) is then given by combining the probability distribution of the QSO overdensity with that of the first PopIII halo of a random cell. From Fig. 4 it is immediately apparent that the advantage of sitting at the top of the QSO overdensity is not sufficient for the first PopIII in this volume to beat all other PopIII in the box. Still one in about 10^3 PopIII progenitors of random M_{qh} cells in the $(720 \text{ Mpc}/h)^3$ box is formed before the QSO progenitor. As there are $\approx 6 \times 10^6$ cells of mass M_{qh} in this volume, we expect from this simple consideration that the PopIII progenitor of the QSO will be formed when already ≈ 6000 other PopIII stars are present in the box, in excellent agreement with the detailed results from the numerical simulation (see Fig. 2).

This result is essentially given by the fact that bright QSOs at $z = 6$ are very rare objects. In fact, if we consider a smaller cosmic volume (e.g. a box of edge 60 Mpc/h)

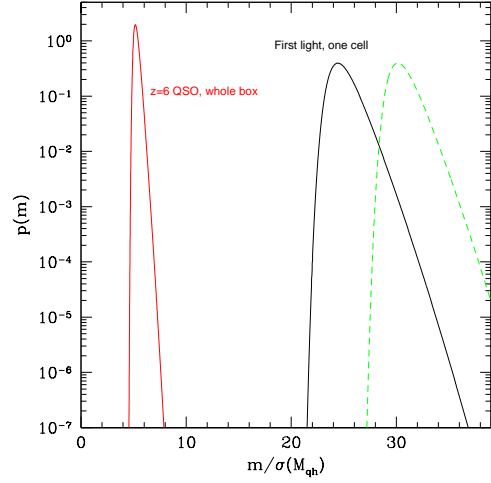


FIGURE 4. From [6]: Probability distribution functions $p(m)$ for the maximum m of k random Gaussian fluctuations representative of mass scale for halos hosting $z = 6$ QSO candidates (red curve) and PopIII stars (black curve). To compute $p(m)$ for QSO hosting halos we have assumed a box of $720 \text{ Mpc}/h$ and a mass scale of $M_{qh} = 4.3 \cdot 10^{12} M_\odot/h$ which implies $k = 180^3$. This curve represents the probability distribution for a sigma peak that at $z \approx 6$ leads to one of the most massive halos in the simulation volume. The curve associated to first light perturbations (solid black, with $M_{fs} = 10^6 M_\odot/h$) is derived using $\sigma_{fs}^2 = \sigma_{M_{fs}}^2 - \sigma_{M_{qh}}^2$ and $k = 160^3$: it represents the probability distribution for the maximum of the sub-grid scale fluctuations at the M_{fs} scale within one cell of the 180^3 volume. The dashed green line represents the probability distribution of the density fluctuation associated to the first PopIII progenitor of a $5.7\sigma(M_{qh})$ peak. m is given in units of $\sigma_{M_{qh}}$.

and repeat the experiment of studying the formation time of the first PopIII progenitor of the most massive $z = 6$ halo, we find different results (see Fig. 5). In this case the cosmic volume considered is significantly smaller, so sitting at the top of the most massive $z = 6$ halo gives a significant relative advantage to PopIII formation at $z > 30$: the PopIII progenitor of the most massive halo is typically within the first 10 to 100 PopIII in the box.

IMBH SEEDS GROWTH

From our investigation it is clear that, before the first PopIII progenitor of the most massive halo at $z = 6$ is born, several thousands of intermediate mass ($m_{BH} \approx 10^2 M_\odot$) black hole seeds are planted by PopIII stars formed in a cosmic volume that will on average host a bright $z = 6$ quasar. Here we investigate with a simple merger tree code what is the fate of the black holes seeds formed up to the formation time of the quasar seed and what are the implications for the observed quasar

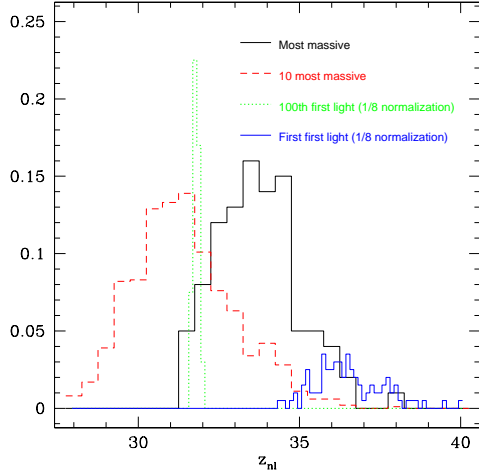


FIGURE 5. From [6]: Like in Fig. 1, but for a smaller box simulation, with volume of $(60 \text{ Mpc}/h)^3$ and $\sigma_8 = 0.75$. Given the limited volume available sitting on the top of the overdensity that will collapse to the largest $z = 6$ halo gives a significant advantage to PopIII halos formed at $z > 30$, which are typically within the first 100 formed in the box.

luminosity function.

We assume Eddington accretion for the BH seeds, so that the evolution of the BH mass is given by:

$$m_{BH} = m_0 \exp[(t - t_0)/t_{sal}], \quad (1)$$

where m_0 is the mass at formation time t_0 and t_{sal} is the Salpeter time [10]:

$$t_{sal} = \frac{\varepsilon m_{BH} c^2}{(1 - \varepsilon)L_{Edd}} = 4.507 \cdot 10^8 \text{ yr} \frac{\varepsilon}{(1 - \varepsilon)}, \quad (2)$$

where ε is the radiative efficiency.

If $\varepsilon \approx 0.1$ there has been enough time to build up a $z \approx 6$ supermassive black hole with mass $m_{BH} > 10^9$ starting from a PopIII remnant formed at $z > 40$. This highlights that only a minor fraction of the PopIII BH seeds formed before $z = 40$ can accrue mass with high efficiency, otherwise the number density of supermassive black holes at low redshift would greatly exceed the observational constraints. The first BH seeds in the box are distant from each other, so they evolve in relative isolation, without possibly merging among themselves. Therefore other mechanisms must be responsible for quenching accretion of the first BH seeds. Interestingly if we were to assume that accretion periods are Poisson distributed in time for each seed, we would not be able to explain the observed power law distribution of BH masses at $z < 6$ around the high mass end. A Poisson distribution would in fact give too little scatter around the median value and a sharp (faster than expo-

ponential) decay of the displacements from the mean accreted mass. An exponential distribution of the accretion efficiency is instead required to match the observed BH mass function. In addition, it is necessary to assume that the duty cycle of the BH accretion is roughly proportional to the mass of the halo it resides in. To explore this possibility we follow the merging history of PopIII halos formed at $z = 40$ by means of a merger-tree code. We implement a BH growth based on Eq. 2, but at each step of the tree we limit the BH mass to $m_{BH} \leq \eta m_{bar}$, where m_{bar} is the total baryon mass of the halo that hosts the BH. If $\eta \approx 6 \cdot 10^{-3}$ (like in [11]), then we obtain an expected mass for the BH powering bright $z = 6$ quasar of $\approx 5 \cdot 10^9 M_\odot$, which is in agreement with the observational constraints from SDSS quasars [2]. By fitting a power law function to the BH mass function in the range $[0.055 : 0.2] \cdot 10^{10} M_\odot$ we obtain a slope $\alpha \approx -2.6$, while the slope is $\alpha \approx -3.7$ in the mass range $[0.2 : 1.0] \cdot 10^{10} M_\odot$, a value that is consistent within the 1σ error bar with the slope of the bright end of the quasar luminosity function measured by [2].

CONCLUSION

We study the link between the first PopIII halos collapsed in a simulation box and the most massive structures at $z \approx 6$, with the aim of establishing the relationship between the first intermediate mass black holes created in the universe and the super-massive black holes that power the emission of bright $z = 6$ quasars. We show that almost no correlation is present between the sites of formation of the first few hundred $10^6 M_\odot/h$ halos and the most massive halos at $z \leq 6$ when the simulation box has an edge of several hundred Mpc . Here the PopIII progenitors (halos of mass $M_{fs} \approx 10^6 M_\odot$) of massive halos at $z \leq 6$ formed from density peaks that are $\approx 1.5\sigma(M_{fs})$ more common than that of the *first* PopIII star in the $(720 \text{ Mpc}/h)^3$ simulation box. These halos virialize around $z_{nl} \approx 40$, to be compared with $z_{nl} \geq 48$ of the *first* PopIII halo.

This has important consequences. We show that, if bright quasars and supermassive black holes live in the most massive halos at $z \approx 6$, then their progenitors at the $10^6 M_\odot$ mass scale are well within the PopIII era, regardless of the PopIII termination mechanism. On the other hand, if the m_{BH}/σ relationship is already in place at $z = 6$, then bright quasars are not linked to the remnants of the very first intermediate mass black holes (IMBHs) born in the universe, as their IMBH progenitors form when already several thousands of PopIII stars have been created within the typical volume that hosts a bright $z = 6$ quasar. The IMBH seeds planted by this very first PopIII stars have sufficient time to grow up to

$m_{BH} \in [0.2 : 1] \cdot 10^{10} M_{\odot}$ by $z = 6$ if we assume Eddington accretion with radiative efficiency $\varepsilon \leq 0.1$. Instead, quenching of the BH accretion is required for the seeds of those PopIII stars that will not end up in massive halos at $z = 6$, otherwise the number density of supermassive black holes would greatly exceed the observational constraints. One way to obtain growth consistent with the observations is to limit the accreted mass at a fraction $\eta \approx 6 \cdot 10^{-3}$ of the total baryon halo mass. This gives a slope of the BH mass function $\alpha = -3.7$ in the BH mass range $m_{BH} \in [0.2 : 1] \cdot 10^{10} M_{\odot}$, which is within the 1σ uncertainty of the slope of the bright end of the $z = 6$ quasar luminosity function ($\alpha \approx -3.5$) measured by [2].

Another important point highlighted by this study is that rich clusters do not preferentially host the remnants of the first PopIII stars. In fact the remnants of the first 100 Pop-III stars in our medium sized simulation box (volume of $(512 Mpc/h)^3$) end up at $z = 0$ on halos that have a median mass of $3 \cdot 10^{13} M_{\odot}/h$. This suggests caution in interpreting the results from studies that select a specific volume of the simulation box, like a rich cluster, and then progressively refine smaller and smaller regions with the aim of hunting for the first lights formed in the whole simulation (see e.g., [4, 5]). Only by considering refinements over the complete volume of the box the rarity and the formation ranking of these progenitors can be correctly evaluated.

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